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Source Assessment Agricultural Open Burning, State of the Art

Monsanto Research Corp, Dayton, Ohio

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16. ABSTRACT The report summarizes reported data on air emissions from agricultural open burning, used in the U.S. for field sanitation, residue removal, and residue disposal. Using estimated emission factors derived from limited literature data, emissions were found to constitute 0.61%, 0.50%, 0.65%, and 0.06% of the national emissions of particulates, HC, CO, and NOx, respectively. Fifteen states have emissions of at least one criteria pollutant from this source which exceed 1% of the state total emissions of that pollutant. Source severity was found to be 1 for HC, 0.2 for POM, and less than 0.1 for other pollutants. (Source severity is defined as the ratio of the time-averaged maximum ground level concentration of a pollutant emitted from a representative source to the primary ambient air quality standard for criteria pollutants or to a corrected TLV for noncriteria pollutants.) Control technology in agricultural open burning consists of practicing fire and fuel management to reduce pollutant emissions. Among alternatives to controlling emissions from open burning are the combination of mobile field sanitation and straw utilization, and incorporation of wastes into the soil. Despite the continuing growth in crop harvest, agricultural open burning has been declining primarily due to increasing concern about air pollution from open burning and the refinement of associated agricultural practices.

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Engineering	Nitrogen Oxides	Open Burning	02C
Land Development		Emission Factors	
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SOURCE ASSESSMENT: AGRICULTURAL OPEN BURNING State of the Art

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PREFACE

The Industrial Environmental Research Laboratory (IERL) of EPA has the responsibility for insuring that pollution control technology is available for stationary sources to meet the requirements of the Clean Air Act, the Federal Water Pollution Control Act and solid waste legislation. If control technology is unavailable, inadequate, uneconomical or socially unacceptable, then financial support is provided for the development of the needed control techniques for industrial and extractive process industries. The Chemical Processes Branch of the Industrial Processes Division of IERL has the responsibility for investing tax dollars in programs to develop control technology for a large number (>500) of operations in the chemical industries.

Monsanto Research Corporation (MRC) has contracted with EPA to investigate the environmental impact of various industries which represent sources of pollution in accordance with EPA's responsibility as outlined above. Dr. Robert C. Binning serves as MRC Program Manager in this overall program entitled, "Source Assessment," which includes the investigation of sources in each of four categories: combustion, organic materials, inorganic materials, and open sources. Dr. Dale A. Denny of the Industrial Processes Division at Research Triangle Park serves as EPA Project Officer. Reports prepared in the Source Assessment Program are of two types: Source Assessment Documents, and State of the Art Reports.

Source Assessment Documents contain data on emissions from specific industries. Such data are gathered from the literature, government agencies and cooperating companies. Sampling and analysis are also performed by the contractor when the available information does not adequately characterize the source emissions. These documents contain all of the information necessary for IERL to decide whether a need exists to develop additional control technology for specific industries.

State of the Art Reports include data on emissions from specific industries which are also gathered from the literature, government agencies and cooperating companies. However, no extensive sampling is conducted by the contractor for such industries. Sources in this category are considered by EPA to be of insufficient priority to warrant complete assessment for control technology decision making. Therefore, results from such studies are published as State of the Art Reports for potential utility by the government, industry, and others having specific needs and interests.

This study was undertaken to provide information on air emissions from agricultural open burning. In this project, Dr. R. A. Venezia served as EPA Project Leader.

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SYMBOLS

Symbol	Definition
a	Flame height
e	2.72
F	Primary ambient air quality standard for criteria pollutants; corrected TLV (i.e., TLV × 8/24 × 1/100) for noncriteria pollutants
H	Effective emission height
k	A system parameter for estimation of effective emission height
Q_h	Heat emission rate relative to ambient temperature
Q_m	Mass emission rate
S	Source severity = $\frac{\bar{x}_{max}}{F}$
t_1	Averaging time
t_2	Burning duration
t_{max}	Short-term averaging time (= 3 min)
$\bar{u}$	Average wind speed
x_{max}	Maximum ground level concentration of a pollutant
$\bar{x}_{max}$	Time-averaged maximum ground level concentration of pollutant emitted from a representative source

SECTION 1

INTRODUCTION

Agricultural open burning in the United States is utilised for field sanitation, residue removal and residue disposal. This practice constitutes a source of air pollution. The objective of this work was to assess the environmental impact of agricultural open burning and to produce a State of the Art Report summarizing available data on air emissions from this source. This document was prepared by acquiring and analysing information on: (1) the basic agricultural open burning process; (2) source sites; (3) emissions produced; (4) effects on air quality; (5) the state of the art and future considerations in pollution control technology; and (6) the projected growth and anticipated technological developments in this practice.

In this study, the effects on air quality resulting from agricultural open burning were determined using estimated emission factors derived from limited emission data available in the literature. Major areas identified as needing further characterisation were: (1) sampling and analysis of polycyclic organic matter (POM) emissions, (2) study of emissions from all major types of agricultural burning, such as soybean and tobacco residue, and (3) measurement of trace element emissions.

SECTION II

SUMMARY

Agricultural open burning is usually practiced for the purpose of field sanitation, residue removal, and residue disposal. It was estimated that the amount of agricultural open burning totaled 13.2 x 10^5 metric tons (14.6 x 10^5 tons) in 1973. Most of the burning occurred in the west and south coastal states, and Hawaii. The combined tonnage of agricultural open burning in California, Louisiana, Florida and Hawaii constituted 59% of the national total in 1973.

Burning of agricultural wastes involves a series of repeated pyrolysis and oxidation steps. Due to the poor mixing between fuel and air and the quenching of combustion gases by surrounding air, products of incomplete combustion such as smoke, gaseous hydrocarbons, carbon monoxide, and polycyclic organic matter are emitted in large amounts. Organic nitrogen compounds in the fuel and part of the nitrogen gas present in the high-temperature flame are converted to nitrogen oxides during the burning process. In addition, trace metal elements are also present in the effluent gas because of their content in the wastes.

Emissions from agricultural open burning constitute 0.61%, 0.50%, 0.65%, and 0.06% of the national emissions of particulates,

hydrocarbons, carbon monoxide, and nitrogen oxides, respectively.[a] The following 15 states have emissions of at least one criteria pollutant from agricultural open burning which exceed 1% of the state total emissions of that pollutant: California, Florida, Georgia, Hawaii, Kansas, Louisiana, Mississippi, Montana, Nebraska, North Carolina, North Dakota, Oklahoma, Oregon, South Carolina, and South Dakota.[a]

Source severity (S) was defined to indicate the hazard potential of the emission source:

$$S = \frac{\bar{Y}_{max}}{F}$$

where $\bar{Y}_{max}$ is the time-averaged maximum ground level concentration of each pollutant emitted from a representative source of agricultural open burning, and F is the primary ambient air quality standard for criteria pollutants and is a "corrected" threshold limit value (TVL®·8/24·1/100) for non-criteria pollutants. The representative source was defined as an agricultural field of 10^5 m^2 (25 acres) with a fuel loading of 6.7×10^{-4} metric tons/m^2 (3 tons/acre), a fire propagation rate of 4.6 m/min (15 ft/min), and a fuel heating value of 12.56 MJ/kg (5,400 Btu/lb). In agricultural open burning, the source severity was found to be 1 for hydrocarbons, 0.2 for benzo(a)pyrene (B(a)P),[b] and less than 0.1 for other pollutants. The population influenced by an average ground level concentration ($\bar{Y}$) for which $\bar{Y}/F$·1 and $\bar{Y}/F$·0.1 is far below 20,000 persons for each of the above-mentioned pollutants.

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[a] Based on assumed emission factors.

[b] Other reported POM compounds, which are not suspected carcinogens, are not included in this study.

Control technology in agricultural open burning consists of practicing fire and fuel management to reduce the emission of pollutants. The two most important factors that can be controlled to minimise the emissions are backfire burning and moisture content of the fuel. In addition to the reduction of emissions mentioned above, the effect of emissions can be minimised by using meteorologically controlled burning to maximise the dispersion of pollutants.

Among the alternatives to controlling emissions from open burning are the combination of mobile field sanitation and straw utilisation, and incorporation of wastes into the soil. The latter requires chemical control of weeds, pests, and disease, and the potential environmental impact from these chemicals must be considered.

Despite the continuing growth in crop harvest, agricultural open burning has been declining since 1969. EPA's estimate of burning was 29 x 10^6 metric tons (32 x 10^6 tons) of residues for 1969. This figure dropped to 13.2 x 10^6 metric tons (14.6 x 10^6 tons) for 1973 due to increasing concern about air pollution from open burning, and development of waste utilisation, chemical sanitation, and modern tillage and fertilisation practices.

Although agricultural open burning will decline, burning in several areas of the country will continue (due to unavailability of alternatives) until more effective and less harmful chemical control of pests, weeds, and disease is available and until other economically viable techniques for residue utilisation or disposal are developed.

SECTION III

SOURCE DESCRIPTION

A. CHARACTERISTICS OF AGRICULTURAL OPEN BURNING

Agricultural open burning is a portion of the overall open burning segment of combustion sources of air pollution in this country. This source of emissions includes the burning of residues of field crops, row crops, and fruit and nut crops for at least one of the following reasons: (1) residue removal and disposal at low cost; (2) preparation of farmlands for cultivation; (3) clearing of vines or leaves from field to facilitate harvest; (4) disease control; (5) direct weed control by incineration of weed seeds and some weed plants; (6) indirect weed control by providing clean soil surface for soil-active herbicides; and (7) destruction of certain mites, insects, and rodents. This study of agricultural open burning does not include prescribed burning which is defined as the use of controlled fire in forests and on ranges to reduce the possibility of wildfire and for other management goals.

Most of the crop residues are usually burned just before or sometime after harvesting. Burning of orchard prunings and natural attrition losses in the San Francisco Bay Area of California is limited to the winter and early spring months when the meteorological conditions permit rapid dispersal

and when oxidant levels are normally low. The duration of burning for each field ranges from a few minutes to several hours per year, depending on the size of the field, type of waste, and environmental conditions.

Because of the unavailability of alternatives which can be applied economically and used to serve many purposes, the burning of agricultural wastes still remains as a common practice despite the growing concern about its contribution to air pollution. The 12 states shown in Table 1 either exempted or did not control agricultural open burning as of 1974. In the other 36 states in the continental U.S., burning is controlled in varying degrees.[1] For example, New Jersey, which prohibits all open burning, has the most restrictive regulations. Of the remaining states where some control is imposed, 25 regulate agricultural open burning directly while 10 regulate it only if a nuisance or hazard is involved. Table 2 gives a summary of how each of these states regulates agricultural open burning, how long the regulations have been in effect, and whether or not a regulation change is contemplated.

B. PROCESS DESCRIPTION

1. Source Composition

The types of agricultural wastes subject to open burning include a variety of residues such as rice straw and stubble, barley straw and stubble, wheat residues, orchard prunings

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[1] Walton, J. W. Disposal of Agricultural Waste by Controlled Burning - A Regulatory Viewpoint. (Presented at Special Conference, Air Pollution Control Association, Proc. Control Technology for Agricultural Air Pollutants. Memphis, Tenn. March 1974.)

Table 1. STATES EXEMPTING OR NOT REGULATING AGRICULTURAL OPEN BURNING[a]

State	Exempt	Not regulated	Regulation change pending
Arkansas	X		No
Iowa		X	No
Kansas	X		No
Kentucky	X		
Louisiana	X		No
Maine		X	Yes[b]
Nebraska	X		No
Rhode Island		X	No
Tennessee	X		No
Virginia	X		No
West Virginia		X	No
Wyoming		X	No

[a]After Reference 1, through 1974.
[b]Open burning regulations became effective July 1, 1975.

and natural attrition losses, grass straw and stubble, potato and peanut vines, tobacco stalk, soybean residues, hay residues, sugarcane leaves and tops, and farmland grass and weeds. These various residues consist of chemically different components called cellulose, hemicellulose, lignin and a group of extractables (oils, pigments, minerals, and other organic substances) in different proportions. Another variation in the source composition is the moisture content between different types of waste and in the same type of waste due to different dryness. A typical ultimate analysis of straw is shown in Table 3.[1]

Table 2. STATES REGULATING AGRICULTURAL OPEN BURNING[a]

State	Type regulation: Directly	Type regulation: As nuisance or hazard	Regulated since	Regulation change pending
Alabama		X	1974	No
Arizona	X		1969	No
California	X		1972	No
Colorado	X[b]			
Connecticut	X		1970	No
Delaware	X		1970	No
Florida		X	1971	No
Georgia	X		1968	No
Idaho		X[c]	1969	No
Illinois	X		1970	No
Indiana	X		1970	No
Maryland	X		1969	No
Massachusetts	X		1967	Yes[d]
Michigan	X		1967	No
Minnesota	X		1970	Yes
Mississippi	X		1974	No
Missouri	X		1968	No
Montana	X		1971	No
Nevada		X	1971	Yes[e]
New Hampshire		X	1967	No
New Jersey	ALL OPEN BURNING PROHIBITED		1959	Yes[f]
New Mexico		X	1971	No
New York	X			Yes
North Carolina	X		1971	No
North Dakota	X		1970	No
Ohio	X		1972	Yes
Oklahoma	X		1974	No
Oregon	X		1975	Yes[g]
Pennsylvania		X	1967	No
South Carolina		X	1968	No
South Dakota		X	1972	Yes[h]
Texas	X		1968	No
Utah	X		1969	Yes
Vermont	X			Yes
Washington	X		1971	No
Wisconsin		X	1969	No

[a] After Reference 1.

[b] Burning of ditches, fence rows, and woods loosely regulated until evaluation can be made into whether or not it is a significant source.

[c] Open burning in grass-seed industry regulated directly.

[d] Legislature passed bill suspending air quality control regulations for one month each year for purpose of agricultural management.

[e] Considering adding a one mile distance limit in urban areas.

[f] Legislature is acting to ease restrictions and permit agricultural burning. All open burning is currently prohibited.

[g] Open burning prohibited in Willamette Valley since January 1, 1975. Legislature may ease this restriction and permit grass seed straw burning in some way.

[h] Considering a permit system as soon as more manpower available.

Table 3. A TYPICAL ANALYSIS AND HEATING VALUE OF STRAW[a]

Carbon	36.00%
Hydrogen	5.00%
Oxygen	38.00%
Nitrogen	0.50%
Moisture	15.75%
Ash	4.75%
Heating value	3,997 kcal/kg or 12.56 MJ/kg (5,430 Btu/lb)

The chemical composition of the waste can also be subdivided into combustible and noncombustible components. The latter include inorganic ash and moisture and these are often referred to as inerts. They do not contribute measurably to the energy released upon combustion, but act as a thermal sink and influence the peak temperature achieved during the burning process. The combustible fraction of the solid fuel (the waste subject to burning) consists of volatile and nonvolatile portions. The volatile portion is composed of low molecular weight hydrocarbon compounds. The nonvolatile portion contains high molecular weight carbonaceous material and can be denoted by C_xH_y, usually with $x >> y$.

Organic species other than those containing only carbon and hydrogen (as mentioned above) may be present in either or both the volatile and nonvolatile combustible fractions. Examples are organically bound nitrogen, sulfur, and halogens. Trace metal elements are also present in the waste.

[a] Johnson, A. J., and G. H. Auth. Fuels and Combustion Handbook. McGraw-Hill, New York, 1951.

Their expected relative concentrations in dry grass stubble, normalized to 10,000 for titanium, are shown in Figure 1.[1]

2. Process Mechanism

The burning of agricultural wastes involves a series of repeated steps. First, the volatiles near the surface are evolved and burned, and then the residual solid nonvolatile combustible structure burns out. As fresh unreacted solid is exposed, these two steps are repeated.

The mechanism involved in the evolution and burning of volatiles is shown in Figure 2. There are two types of reactions taking place in this step. They are pyrolysis in the precombustion zone and oxidation in the mixing and combustion zone.[2] In the precombustion zone, pyrolysis takes place in the absence of oxygen. The driving force for these pyrolytic reactions is the countercurrent transport of thermal energy from the mixing and combustion zone.

Pyrolysis is a combination of thermal cracking and condensation, and can occur in both the solid and vapor phases.[3] In the solid phase, hemicelluloses decompose first, then the cellulose, and then the lignin. The extractables evolve on

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[1]Shum, Y. S., and W. D. Loveland. Atmospheric Trace Element Concentrations Associated with Agricultural Field Burning in the Willamette Valley of Oregon. Atmospheric Environment, 8:645, December 1974.

[2]Edwards, J. B. Combustion - Formation and Emission of Trace Species. Ann Arbor Science, Ann Arbor, Michigan, 1974.

[3]Orning, A. A. The Principles of Combustion. In: Principles and Practices of Incineration, Corey, R. C. (ed.). New York, Wiley-Interscience, 1969.

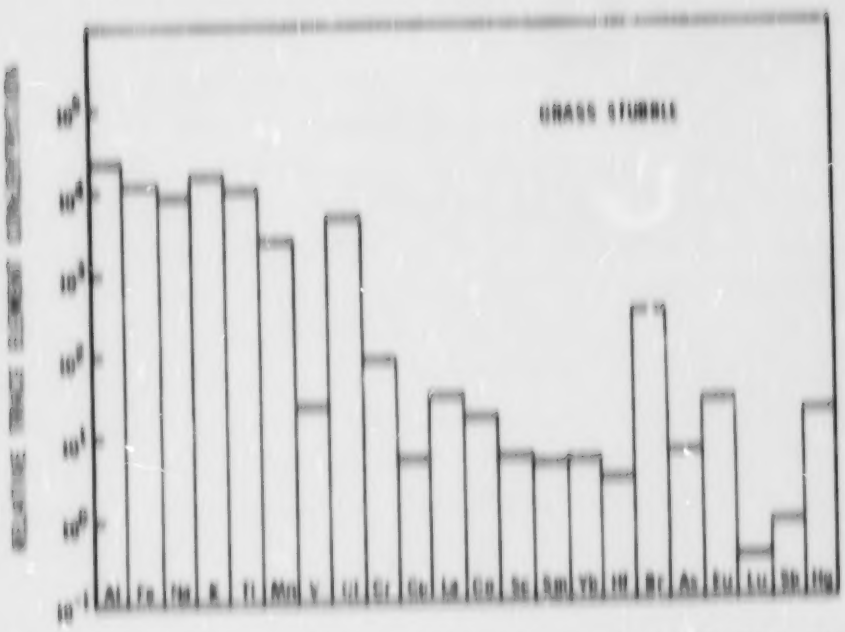

Figure 1. Relative trace element content of dry grass stubble.[3]

Reprinted with permission from W. D. Loveland, Atmospheric Trace Element Concentrations Associated with Agricultural Field Burning in the Willamette Valley of Oregon, December 1974, Pergamon Press.

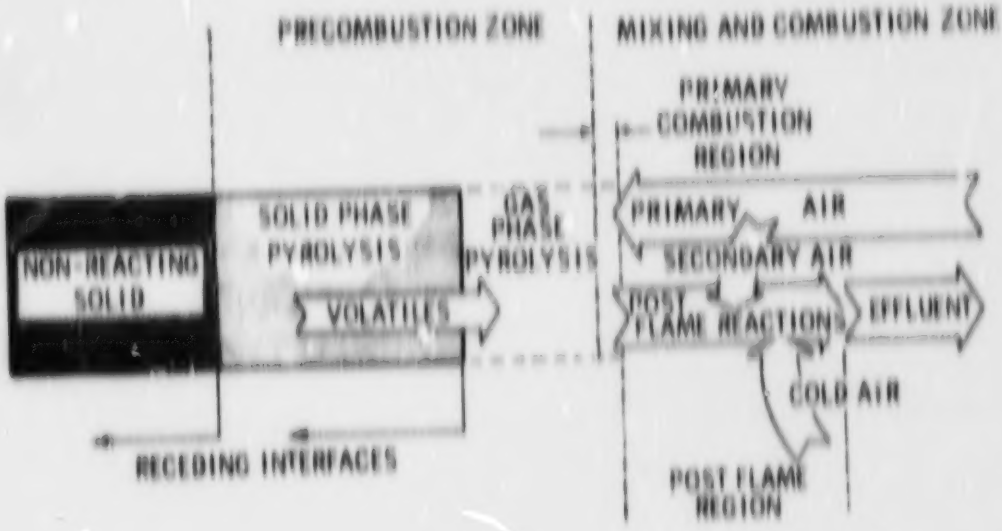

Figure 2. Open burning of solid fuel.[4]

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the basis of their volatility and reactivity at the higher temperatures.[1] The volatile components are vaporized and carried away from the solid surface where they mix with the surrounding air. A diffusion flame is established within the primary combustion region where the mixing of combustibles and oxygen forms a flammable mixture.

Due to the poor mixing between air and fuel in agricultural open burning, there is a region between the fuel surface and the diffusion flame which contains little or no oxygen. Heating of the fuel vapors within this space promotes gas phase pyrolytic reactions. The reactions involved in this space consist of a competition between thermal cracking, producing lighter and more stable products, and condensation reactions, producing heavier molecules. As the condensation goes on, the heavier molecules may be condensed to liquid aerosols which are then converted to solid particles eventually approaching carbon, and hydrogen is produced and burned in the diffusion flame.

Once the particles are formed, their oxidation is a relatively slow process (due to the heterogeneous reactions involved) and the time that it takes for these carbonaceous particles to pass through the oxidation region may be insufficient to oxidize them. In the case of open burning, rapid quenching of the combustion gases by the huge surrounding volume of cold air further enhances the incompleteness of combustion, thus permitting emission of a large amount of smoke and unburned gaseous hydrocarbons in the effluent gas.

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[1] Yamate, G. Development of Emission Factors for Estimating Atmospheric Emissions from Forest Fires. Publication No. EPA 450/3-73-003, October 1972.

The oxidation of unburned gaseous organic compounds and smoke particles continues in the post flame region, provided that sufficient secondary oxygen is present and the temperature is high enough. However, due to the quenching by large unrestricted volumes of cold air, this post flame region becomes relatively small in open burning.

Once the volatiles present near the fuel surface have been evolved, oxidation of the nonvolatile portion of combustible material (often referred to as char) occurs by a different mechanism. This mechanism involves oxygen diffusion to a gas-solid interface where oxidation occurs. This process of "burnout" is a slow one since it involves several sequential mass and heat transfer steps. No smoke is produced in this step of burning.

Once the residual solid structure is burned out and the fresh unreacted solid is exposed, the process described above is repeated until all the wastes are burned.

3. Formation of Pollutants

The poor mixing between fuel and air and the quenching of combustion gases by surrounding air contribute to the emission of smoke, gaseous organic compounds, and carbon monoxide, all of which are products of incomplete combustion.

Smoke is a suspension of very small (submicron) particulates consisting of solid and liquid aerosols. The liquid aerosols are white to brown in color and are formed from partial condensation in the precombustion zone. These particles are emitted in the effluent gas because they are neither ignited nor heated to sufficient temperature to cause continuing pyrolysis. Solid aerosols are black in color and are formed when the liquid aerosols are heated to sufficient temperature

in the absence of oxygen to cause continuing pyrolysis into a solid form.

Another class of pollutants which may be contained in smoke is polycyclic organic matter (POM), sometimes reported by others as polynuclear hydrocarbons. These heavy hydrocarbons, which may have carcinogenic properties, may be formed by a sequence of pyrolytic reactions in the precombustion zone shown in Figure 3. An example of POM formation is illustrated in Figure 3 where two paths are shown for the synthesis of the polycyclic aromatic benzo(a)pyrene.[6,7] The relative tendency for hydrocarbons to form polycyclic species is:

aromatics > cycloolefins > olefins > paraffins

POM's may be emitted as liquid aerosols, condensed on the solid particulates, or vaporized and remain as gases until condensed in the sampling apparatus.

In addition to the particulates of submicron size mentioned above, particulate matter can also be derived from fly ash and fragments of partially burned fuel. However, these particulates are not generally present in sufficient number of particles per unit volume to produce dense smoke.[5]

Thermal cracking and condensation reactions are also the source of a large variety of organic compounds. Any of these compounds that are either not burned or incompletely burned and are not condensed to smoke may escape as gaseous organic compounds. These compounds include aldehydes,

[7]Chakrabarty, B. B., and R. Long. The Formation of Soot and Aromatic Hydrocarbons in Diffusion Flames - Part III. Combustion and Flame, 12:469, May 1968.

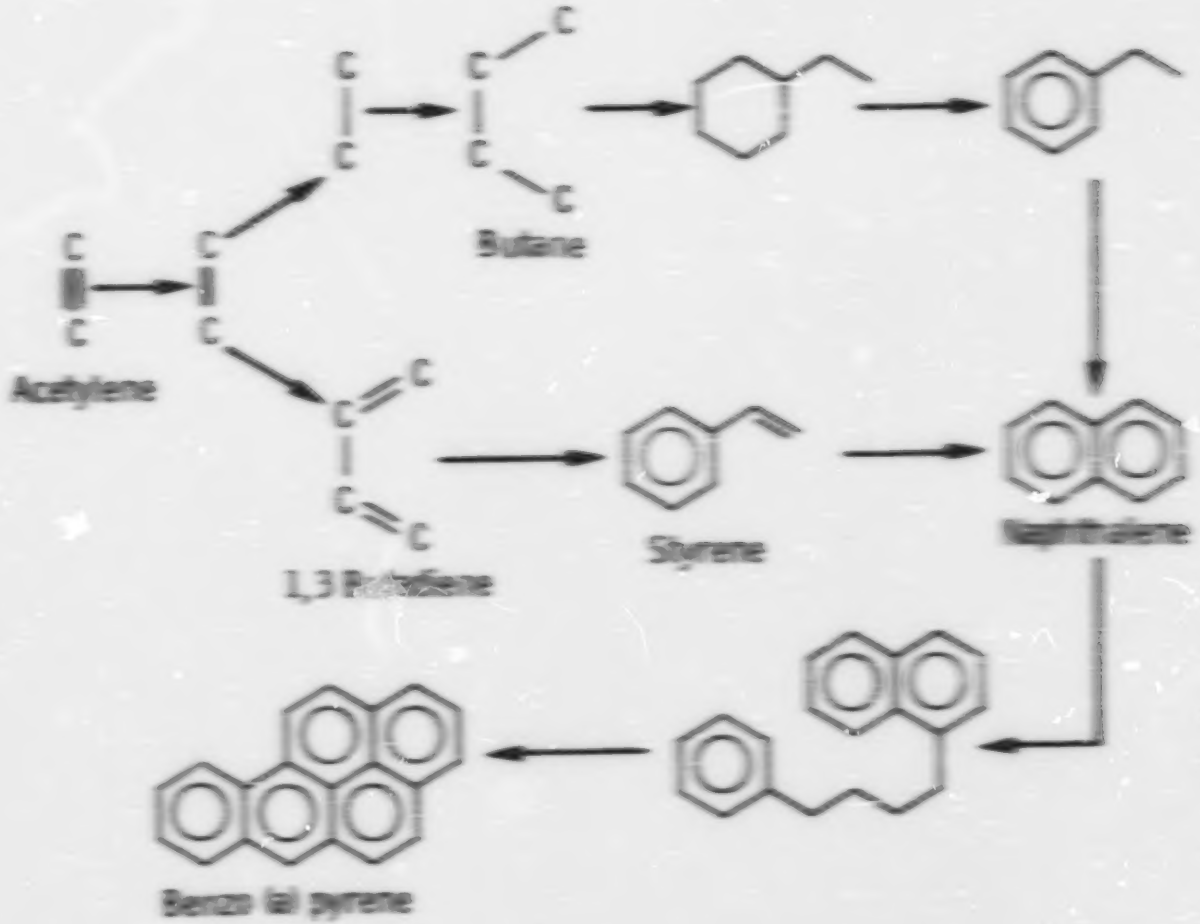

Figure 1. Pyrolytic synthesis of B(a)P.*

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amines, organic acids, ketones, and gaseous hydrocarbons.[8-11] Gaseous hydrocarbons include saturates, unsaturates (olefins, acetylenes, and aromatics), and possibly gaseous polynuclear hydrocarbons. Olefins and aromatic compounds are the main organic constituents in photochemical smog.

Carbon monoxide is formed when the air supply in the combustion zone is below the theoretical requirement. Carbon monoxide also forms by the gasification of smoke particles. Gasification reactions become possible when the environment in the post-flame area becomes reduced due to insufficient secondary oxygen supply. The reactions can be represented by the following two equations:

$$C_{(s)} + CO_2 \rightarrow 2CO \qquad \text{(III-1)}$$

$$C_{(s)} + H_2O \rightarrow CO + H_2 \qquad \text{(III-2)}$$

Note that for simplicity the particulate is depicted as pure carbon. In reality it is CH_y with $y \approx 1.0$.

The residues also have a small content of organic nitrogen compounds. Upon combustion these nitrogen compounds will be oxidized to nitrogen oxides. Due to the high temperature of

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[8]Gerstle, R. W., and D. A. Kemnitz. Atmospheric Emissions from Open Burning. J. Air Poll. Cont. Assoc., 17:324-327, May 1967.

[9]Sandburg, D. V., S. G. Pickford, and E. F. Darley. Emissions from Slash Burning and the Influence of Flame Retardant Chemicals. J. Air Poll. Cont. Assoc., 25:278, March 1975.

[10]Darley, E. F., F. B. Burleson, E. H. Mateer, J. T. Middleton, and V. P. Osterli. Contribution of Burning of Agricultural Wastes to Photochemical Air Pollution. J. Air Poll. Cont. Assoc., 16:685, December 1966.

[11]Boubel, R. W., E. F. Darley, and E. A. Schuck. Emissions from Burning Grass Stubble and Straw. J. Air Poll. Cont. Assoc., 19:497, July 1969.

the flame, nitrogen oxides are also formed by the fixing of nitrogen present in the air.

In the burning process the moisture contained in the waste is simply evaporated along with the combustible volatiles. A fraction of the energy produced by combustion must be expended to vaporize this moisture and heat it to flame temperature. This results in a reduction in flame temperature, and thus a decrease in the formation of nitrogen oxides and an increase in the particulate emissions.

For high moisture contents, especially associated with wet pockets of waste, the vapor pressure of the water may almost equal the atmospheric pressure. Under this extreme condition oxygen is almost excluded from the area near the flame. This insufficiency of oxygen for combustion enhances the emission of pollutants.

C. FACTORS AFFECTING EMISSIONS

Factors affecting the completeness of burning and emission of pollutants can be separated into the three categories listed below where the factors of major importance are indicated by an asterisk (*).

- Environmental variables
  - Air temperature
  - Soil moisture
  - Relative and/or absolute humidity
  - *Wind speed and direction
- Fuel conditions
  - Type of fuel (chemical composition)
  - *Waste moisture content
  - Density of fuel, kg/m^3 (lb/ft^3)

- Fire management
  - Backfire or headfire
  - Fuel loading, kg/m^2 (lb/ft^2)

D. GEOGRAPHICAL DISTRIBUTION

Open burning is one of the principal methods for disposing of agricultural wastes. As late as 1968, it was the most widely accepted method especially in the west, due to its low cost and effectiveness in control of weeds, pests, and disease. However, open field burning has been eliminated in some areas of the country because of the increasing awareness of its contribution to air pollution, the development of waste utilization, chemical control of weeds, pests, and disease, and modern tillage and fertilization practices.

According to a survey made for EPA in 1974, there were 13 states where agricultural open burning was negligible.[12] Since then, Oregon has banned all open burning (as of January 1, 1975). However, there are strong indications that the state legislature of Oregon will reverse their decision and burning will continue for several years.[3,13]

Table 4 gives a summary of agricultural open burning data for the 37 states where agricultural open burning is practiced significantly. Data on acres burned and fuel loading were obtained from Reference 12 for 16 states; and the amount of burning for 2 states was obtained from References 14 and 15, as shown in the table. These data were reported in non-metric units.

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[12]Yamate, G. Emissions Inventory from Forest Wildfires, Forest Managed Burns, and Agricultural Burns. Publication No. EPA-450/3-74-012, November 1974.

[13]Personal communication, H. M. Patterson, Department of Environmental Quality, Portland, Oregon, 1975.

The total amount of burning for the remaining 19 states was determined from the difference between national total[15] and the total of the above-mentioned 18 states. This total amount was then proportionated according to the crop acreage for each state to obtain the amount of burning for that state. Sample calculations of the amount burned and the area burned are shown in Appendix A.

As shown in Table 4, California, Louisiana, Florida, and Hawaii are the major agricultural open burning states, each burning in excess of 1,600,000 metric tons/yr. The tonnage of burning in these states constitutes 59% of the national total. As shown in Table 4, six states burn 400,000 to 1,000,000 metric tons/yr, twelve states burn 100,000 to 400,000 metric tons/yr, and fifteen states burn less than 100,000 metric tons/yr. Most of the burning occurs in the west and south coastal states.

Since considerable agricultural open burning occurs in states with low population density (such as North Dakota and Kansas), a simple exposure factor was used to indicate the combination effect of amount of burning and state population. The exposure factor was defined as follows:

$$\text{Exposure factor} = (\text{amount burned in the state, in thousands of metric tons per year}) \times (\text{state population fraction}) \qquad \text{(III-3)}$$

The state population fraction is the ratio of the state population to the national population. The exposure factor represents the relative significance of agricultural open burning for each state and is shown in Table 4.

Table 4. SUMMARY OF AGRICULTURAL OPEN BURNING DATA (1973)

State	Area burned (10^3 m^2/yr [10^3 acres/yr])		Fuel loading (10^{-3} [kg/m^2] [tons/acre])		Amount burned (10^3 metric tons/yr [10^3 tons/yr])		Emission factor (lb/ton)
Alabama	15.	69. [1]	1	2 [1]	1.5	(16)	3.14
Arizona[2]	4.5	11.	4	21	2	(22)	0.18
Arkansas[2]	25.	64.	4	21	115	(126)	1.09
California	105.	264. [1]	7	37 [1]	2,070	(2,280)	180.9
Colorado[2]	17.	70.	4	21	141	(156)	1.51
Delaware	0.1	.2 [1]	22	(24) [1]	2	(2)	0.01
Florida	105.	270. [1]	11	57 [1]	1,716	(1,890)	57.65
Georgia	35.5	91. [1]	3	15 [1]	883	(974)	20.6
Hawaii	66.7	168. [1]	21	(111) [1]	1,375	(1,515)	6.67
Idaho	4.8	12. [1]	4	21 [1]	33	(36)	0.08
Kansas	195.	500. [1]	3	15 [1]	144	(160)	5.08
Kentucky[2]	13.	33.	3	15	51	(56)	0.83
Louisiana	141.	350. [1]	11	57 [1]	1,584	(1,746)	55.21
Maine	15.	39. [1]	2	11 [1]	33	(36)	0.17
Maryland	0.6	1.6 [1]	11	57 [1]	7	(8)	0.1
Massachusetts[2]	0.6	1.5	5	26	8	(9)	0.1
Michigan[2]	41.	94.	4	21	83	(92)	0.1
Minnesota[2]	61.7	153.	4	21	274	(302)	5.15
Mississippi	135.	340.	4	21 [1]	611	(673)	9.78
Missouri[2]	69.9	180.	4	21	281	(310)	5.16
Montana	35.	86.	4	21 [1]	153	(169)	0.13
Nebraska[2]	67.8	167.	4	21	301	(332)	5.24
Nevada	0.9	2. [1]	4	21 [1]	4	(4)	0.03
New Hampshire	0.9	2. [1]	4	21 [1]	4	(4)	0.03
North Carolina	120.	301. [1]	4	21 [1]	519	(572)	15.1
North Dakota[2]	81.	202.	4	21	438	(484)	1.31
Ohio	28.	70.	4	21	143	(158)	1.87
Oklahoma[2]	30.	80.	4	21	161	(178)	2.83
Oregon	107.	264. [1]	4	21 [1]	418	(461)	4.0
Pennsylvania[2]	15.	38.	4	21	83	(91)	1.52
South Carolina[2]	8.	21.	4	21	38	(42)	0.69
South Dakota[2]	55.	135.	4	21	305	(337)	0.87
Tennessee[2]	14.	35.	4	21	61	(68)	1.1
Utah[2]	3.3	8.	4	21	31	(35)	0.59
Washington	61.	151. [1]	7	37 [1]	256	(282)	3.36
Wisconsin[2]	32.	80.	4	21	145	(160)	1.16
Wyoming[2]	7.3	18.	4	21	18	(20)	0.06
National total	1,159.	2,864.			11,243	(12,400)[3]	

[1] Calculations shown in Appendix A.

[2] Air Pollution EM Group Inventory for the State of Montana. EPA Publication No. EM EPA 101, 1971.
[2] Air Pollution Emission Inventory for the State of New Mexico. EPA Publication No. EM EPA 103, 1971.
[3] Personal communication. Charles Mann. ORAPS, EPA, Durham, North Carolina, 1975.

The seasons for burning and the types of waste burned in the 10 states with annual burning greater than 400,000 metric tons (441,000 tons) are shown in Figure 4.

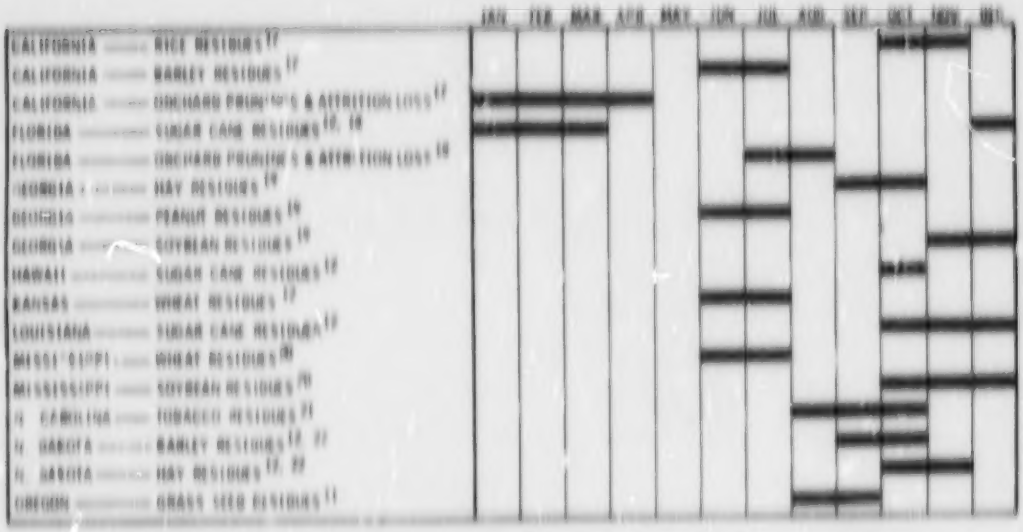

Figure 4. Illustration of agricultural open burning seasons in the ten states with annual burning greater than 400,000 metric tons.

[17]Agricultural Solid Waste Disposal and Management in California. Report of the Research Task Group, Division of Agricultural Sciences, University of California, Berkeley, California, 1973.

[18]Department of Pollution Control, Tallahassee, Florida, 1975.

[19]Environmental Protection Division, Department of Natural Resources, Atlanta, Georgia, 1975.

[20]Mississippi Air and Water Pollution Control Commission, Jackson, Mississippi, 1975.

[21]Office of Water and Air Resources, Department of Natural and Economic Resources, Raleigh, North Carolina, 1975.

[22]Usual Planting and Harvesting Dates, Agricultural Handbook No. 283, U.S. Department of Agriculture, Washington, D.C., 1972.

SECTION IV

EMISSIONS

A. SELECTED POLLUTANTS AND THEIR CHARACTERISTICS

The process mechanism and the formation of pollutants in agricultural open burning have been described in detail in Sections III.B.2 and III.B.3. Based on that information, the major pollutants resulting from agricultural open burning are: (1) particulates, derived from fly ash and partially burned fuel; and smoke from incomplete combustion; (2) hydrocarbons, from thermal cracking and condensation reactions; (3) carbon monoxide, from incomplete combustion and from gasification of smoke particles; (4) nitrogen oxides, from oxidation of organic nitrogen compounds and from fixation of nitrogen present in air; and (5) polycyclic organic matter (POM), present in smoke and formed by pyrolytic reactions in the precombustion zone. In addition, trace metal elements including nickel, chromium, beryllium, cadmium, copper, selenium, arsenic, mercury, titanium, manganese, and antimony can be emitted. Due to their adverse health effects and atmospheric reactivity which are described below, the above-mentioned pollutants were selected for consideration in this study. Sulfur oxides are not included here because their emissions from agricultural open burning are negligible.[1]

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[1] Compilation of Air Pollutant Emission Factors (Revised). U.S. Environmental Protection Agency, Office of Air Programs, Research Triangle Park, N.C. OAP Publication No. AP-42. April 1973.

The health effects and atmospheric stability of emissions from agricultural open burning are essentially the same as those generally reported for air pollution sources, and these are presented in Table 5. Due to insufficient data on trace element emissions, the characteristics of these pollutants are not listed in Table 5.

Most of the particulate emissions are solid and liquid aerosols of submicron size. In the burning of rice straw, the mass median diameter of particulate emissions ranged from 0.11 to 0.13 μm.[24] The data also showed a mass median diameter of 0.025 to 0.10 μm for chloroform extractable particulates and 0.025 μm for chloroform insoluble particulates. Chloroform extractable particulates may be composed of liquid hydrocarbon aerosol emitted during the pyrolysis stage of the burning process. The chloroform insoluble particles presumably consist of carbon particles and fly ash. The small size of particulate matter emitted by agricultural open burning was also reported in another study and the mean size was found to be 0.5 μm for the burning of grass seed residues.[25]

These fine particulates have the following effects: (1) they absorb and scatter light and thus reduce visibility; (2) they can penetrate the collection mechanisms of the human respiratory tract and lodge in the alveolar regions of the lungs; (3) some potentially hazardous trace elements may be enriched

[24] Goss, J. R., and G. E. Miller. Study of Abatement Methods and Meteorological Conditions for Optimum Dispersion of Particulates from Field Burning of Rice Straw - Spring Open Field Burning Trials. Publication No. PB 235 796, June 1971.

[25] Heland, B. R., and R. W. Boubel. A Study of Field Burning Under Varying Environmental Conditions. J. Air Poll. Cont. Assoc., 16:481, September 1966.

Table 5. CHARACTERISTICS OF EMISSIONS FROM AGRICULTURAL OPEN BURNING

Compound	Health effects	Atmospheric stability
Particulate	Unknown	Stable
NO_x	Dangerous irritant to lungs	Contributes to photochemical smog
CO	Asphyxiating gas	Stable
Hydrocarbons	Simple asphyxiants	Contributes to photochemical smog
POM	Carcinogenic (suspected)	Stable

in these submicron particles; and, (4) most of the particles have the potential of remaining in the atmosphere for an extended period of time, unless removed by rain or snowfall, or by the slow process of coagulation and subsequent gravitational settling.

B. EMISSION FACTORS

The quantities of emissions produced per unit of waste burned have been reported by several authors. Table 6 is a compilation of the information gathered from the literature and includes only those articles containing emission factors or data that can be used to calculate emission factors. Blanks in Table 6 indicate that the particular data are not reported in the cited references.

Particular attention was given to the data on the emission of polycyclic organic matter (POM). The POM data shown in the table are only those for benzo(a)pyrene. Although 10 more POM compounds have been identified and measured in the emissions from burning of grass clippings, leaves, and branches,[8,26,27] these 10 compounds were not included in the table because they do not have potential carcinogenic activity[28] (defined as activity on animal tests). In addition to the 11 compounds mentioned above, there might be large

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[26] Hangebrauck, R. P.; D. J. Von Lehmden, and J. E. Meeker. Emissions of Polynuclear Hydrocarbons and Other Pollutants from Heat-Generation and Incineration Processes. J. Air Poll. Cont. Assoc.; 14:267; July 1964.

[27] Hangebrauck, R. P.; D. J. Von Lehmden, and J. E. Meeker. Sources of Polynuclear Hydrocarbons in the Atmosphere. U.S. Department of Health, Education, and Welfare. Public Health Service Publication No. 999-AP-33, 1967.

[28] Particulate Polycyclic Organic Matter. National Academy of Sciences, Washington, D.C. 1972.

amounts of other polynuclear aromatic hydrocarbons and their alkyl derivatives, and polynuclear heterocyclic hydrocarbons present in the emissions. Some of these compounds have been found to be carcinogenic in animal studies.[11,12] However, the amount of these pollutants in the emissions is unknown at the present time and therefore, the actual POM emission may be higher than the data shown in the table.

The reported data on emissions of trace metal elements from agricultural open burning is limited. The emission factors for five elements from burning of sugarcane residue are listed in Table 6.[11] In another study, the emission of selenium oxide in the burning of sugarcane has been reported.[13] However, the data reported as selenium content in the smoke cannot be used to calculate meaningful emission factors due to the lack of data on CO_2 concentration, air flow rate and temperature.

In a recent study,[1] the concentration of 26 trace elements in gross air particulate samples taken from the burning of residues from grass seed production were reported. It was concluded that the atmospheric trace element abundances associated with field burning were due to the trace element content of the stubble being burned. The trace elements concentrate in the larger sized particles having diameters >11 μm. These data did not permit an evaluation of emissions in terms of units of pollutant per unit of waste burned.

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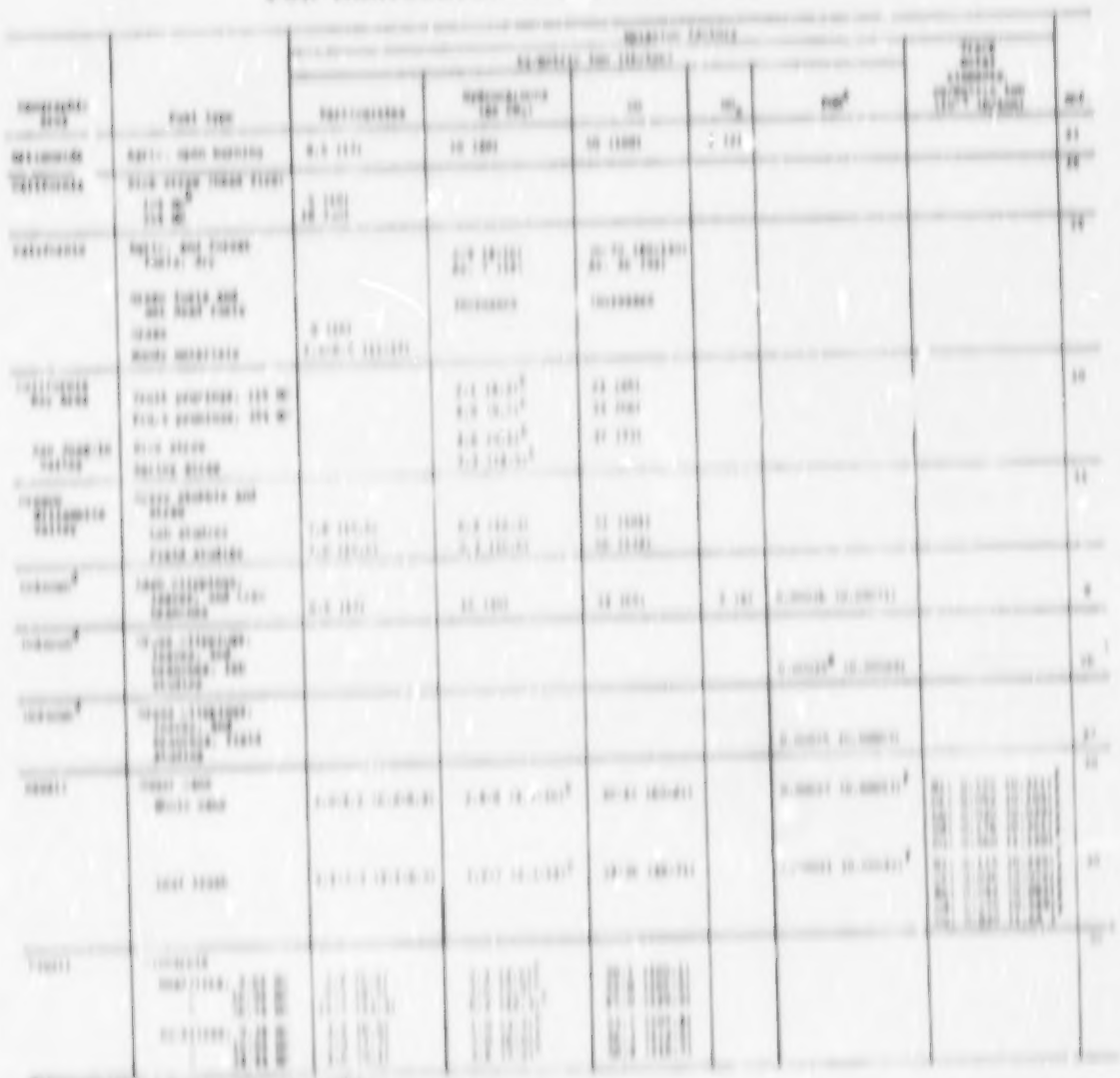
[11] Epstein, S. S., M. Small, J. Kaplan, N. Mantel, H. L. Falk, and E. Sawicki. Photodynamic Bioassay of Polycyclic Air Pollutants. Arch. Environ. Health, 7:531, November 1963.

[12] Hartwell, J. L. Survey of Compounds Which Have Been Tested for Carcinogenic Activity. U.S. Public Health Service Publication No. 149, 1951.

[13] Shendrikar, A. D., and P. W. West. Determination of Selenium in the Smoke from Trash Burning. Environmental Letters, 5:29, January 1973.

Table 6. PUBLISHED AND CALCULATED EMISSIONS FACTORS FOR AGRICULTURAL [illegible] BURNING



The following emission factors, selected and assumed as representative of agricultural open burning, were used in the calculations of ground level concentration, mass emissions, and affected population in Section IV.D:

Pollutant	Emission factor, kg/metric ton (lb/ton)	
Particulates[23]	8.5	(17)
Total hydrocarbons (as CH_4)[23]	10	(20)
Carbon monoxide[23]	50	(100)
Nitrogen oxides[23]	1	(2)
POM		
Benzo(a)pyrene[8,26,27,10]	0.00029	(0.00058)
Trace metal elements		
Nickel[10]	0.14×10^{-3}	(0.27×10^{-3})
Chromium[10]	0.044×10^{-3}	(0.088×10^{-3})
Beryllium[10]	0.031×10^{-3}	(0.061×10^{-3})
Cadmium[10]	0.23×10^{-3}	(0.45×10^{-3})
Copper[10]	0.70×10^{-3}	(1.4×10^{-3})

C. DEFINITION OF REPRESENTATIVE SOURCE

A representative source of agricultural open burning was defined in order to determine the source severity which is described in Section IV.D. This representative source consists of an agricultural field of 10^5 m^2 (25 acres)[11,1]

[10]Moore, J., and C. D. Wolbach, Source Sampling of Sugarcane Burning, Texas Air Control Board, Source Sampling Section, May 1974.

with a fuel loading of 6.7×10^{-4} metric tons/m^2 (3 tons/acre),[24] a fire propagation rate of 4.6 m/min (15 ft/min),[24] and a fuel heating value of 12.56 MJ/kg (5,400 Btu/lb).[2] The following assumptions were made to characterize the burning conditions: (1) burning starts from one side of the square field; (2) there is a 20% heat loss to soil, ash, and water evaporation; (3) flame height is 2 m (7 ft); and (4) wind speed equals the national average of 4.5 m/s (10 miles/hr).

D. SOURCE SEVERITY

1. Maximum Ground Level Concentration

The maximum ground level concentration (χ_{max}) of each pollutant resulting from agricultural open burning was estimated by Gaussian plume dispersion meteorology. χ_{max} values for the average (representative), best, and worst cases (see Appendix B.4) are shown in Table 7. For comparison, the TLV and the ambient air quality standard for the criteria pollutants are also listed.

The following formula was used for the calculation of χ_{max}:

$$\chi_{max} = \frac{2Q_m}{e\bar{u}H^2e\pi} \qquad \text{(IV-1)}$$

where Q_m = mass emission rate, g/s
$\bar{u}$ = average wind speed, m/s
H = effective emission height, m
e = 2.72

The effective emission height was estimated by the following equation (shown in the units reported by the authors referenced in Appendix B):

Table 7. MAXIMUM GROUND LEVEL CONCENTRATION AND SEVERITY FACTOR OF DIFFERENT EMISSIONS[a]

Emission	C_{max}, g/m³		$\bar{C}_{max}$, g/m³	TLV_{8h},[b] g/m³	Ambient air[c] standard, g/m³	Severity
	Range	Average				
Particulates	$5 \times 10^{-5} - 5 \times 10^{-4}$	7×10^{-4}	2×10^{-8}	1.0×10^{-1}	2.6×10^{-5}	0.66
Hydrocarbons	$6 \times 10^{-5} - 6 \times 10^{-4}$	8×10^{-4}	2×10^{-6}	4.72×10^{-1}	1.6×10^{-6}	1
CO	$3 \times 10^{-4} - 3 \times 10^{-3}$	4×10^{-3}	2×10^{-8}	5.5×10^{-2}	4.0×10^{-6}	0.66
NO_x	$6 \times 10^{-4} - 6 \times 10^{-3}$	8×10^{-3}	6×10^{-8}	9.0×10^{-4}	1.0×10^{-6}	0.00857
HCN						
Ni(CO)₄	$2 \times 10^{-5} - 2 \times 10^{-4}$	2×10^{-4}	7×10^{-13}[d]	1.0×10^{-6}	NA[e]	0.2
Trace metal elements						
Ni	$8 \times 10^{-14} - 8 \times 10^{-13}$	1×10^{-13}	3×10^{-16}	7×10^{-6}	NA	1×10^{-6}
Cr	$2 \times 10^{-13} - 2 \times 10^{-12}$	4×10^{-12}	1×10^{-14}	5×10^{-6}	NA	6×10^{-11}
Be	$2 \times 10^{-15} - 2 \times 10^{-14}$	3×10^{-14}	7×10^{-17}	2×10^{-6}[f]	NA	1×10^{-6}
Cd	$1 \times 10^{-13} - 1 \times 10^{-12}$	2×10^{-12}	5×10^{-14}	2×10^{-6}[g]	NA	8×10^{-10}
Cu	$8 \times 10^{-13} - 8 \times 10^{-12}$	6×10^{-12}	2×10^{-13}	1×10^{-6}[h]	NA	5×10^{-11}

[a] Calculations are based on assumed emission factors.

[b] 24-hour average.

[c] 1-hour average.

[d] 1-hour average.

[e] Annual average.

[f] Not applicable.

[g] TLV for nickel carbonyl.

[h] TLV for an oxide chromic, chromous salts.

[i] TLV for elemental beryllium.

[j] TLV for cadmium metal oxides.

[k] TLV for copper dusts and mists.

[1] Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment. American Conference of Governmental Industrial Hygienists, 1971.

[2] National Primary and Secondary Ambient Air Quality Standards. U.S. Environmental Protection Agency. Federal Register, 36, April 1971.

$$H = kQ_h^{\frac{1}{4}} / B + a \qquad \text{(IV-2)}$$

where k = a system parameter, $m^2/kcal^{1/4}\ s^{3/4}$
Q_h = heat emission rate relative to ambient temperature, kcal/s
a = flame height, m

Equation IV-2 was derived for particular application to agricultural open burning. The derivation of Equation IV-2 and the evaluation of system parameter k are given in Appendix B. Q_m and Q_h are functions of field geometry, fire propagation rate, fuel loading, and emission factor. Q_h is also proportional to the heating value of the fuel.

The input data for and a sample calculation of Q_m, Q_h, H, and χ_{max} are also given in Appendix B.

2. Severity Factor

To obtain an indication of the hazard potential of the emission source, the source severity (S) was defined as:

$$S = \frac{\overline{\chi}_{max}}{F} \qquad \text{(IV-3)}$$

where $\overline{\chi}_{max}$ is the time-averaged maximum ground level concentration of each pollutant emitted from a representative source of agricultural open burning (see section IV.C), and F is the primary ambient air quality standard for criteria pollutants and is a "corrected" threshold limit value (TLV·8/24·1/100) for noncriteria pollutants. This severity

factor represents the ratio of time-averaged maximum ground level exposure to the hazard level of exposure for a particular pollutant.

$\bar{x}_{max}$ is the maximum ground level concentration (x_{max}) averaged over a given period of time. The averaging time is 24 hours for noncriteria pollutants. For criteria pollutants, averaging times are the same as those used in the primary ambient air quality standards.

If t_1 represents the averaging time and t_2 represents the burning duration, the relationship between $\bar{x}_{max}$ and x_{max} can be expressed by the following two equations for agricultural opening burning:

If $t_1 \leq t_2$

$$\bar{x}_{max} = x_{max}\left(\frac{t_{max}}{t_1}\right)^{0.17} \qquad \text{(IV-4)}$$

If $t_1 > t_2$

$$\bar{x}_{max} = x_{max}\, t_2^{0.83} t_{max}^{0.17}/t_1 \qquad \text{(IV-5)}$$

where t_{max} is the short-term averaging time for which equation (IV-1) is valid. The derivation of equations (IV-4) and (IV-5) is given in Appendix B.3.

$\bar{x}_{max}$ and source severity for each pollutant emitted from burning of a field under average conditions (see Appendix B.4) are shown in the third and last column of Table 7, respectively. It can be seen that the source severity is 1 for hydrocarbons, between 0.1 and 1 for B(a)P, and below 0.1 for other pollutants. It should be emphasized that these calculations were based on the assumed emission factors mentioned in Section IV.B. There

might also be emission of other toxic POM compounds and trace metal elements for which the emission factors are not available at the present time.

3. Contribution to Total Air Emissions

The contribution of agricultural open burning to statewide and nationwide air emissions was measured by the ratio of mass emissions from this source to the total emissions from all sources.

The mass emissions of criteria pollutants resulting from agricultural open burning were calculated by multiplying the emission factors by the total burning done in the state. The mass emission for each pollutant is shown in Table 8 for the states where agricultural open burning is usually practiced, along with the nationwide emissions. There are no figures for sulfur oxides in Table 8 because the emission of sulfur oxides from agricultural open burning is negligible.[12]

Table 9 gives the ratios of criteria pollutant emissions resulting from agricultural open burning to the total criteria pollutant emissions in each corresponding state and the nation. The total criteria pollutant emissions for each state were obtained from the 1972 National Emission Report. The states with at least one ratio greater than 1% are noted in the table. On a nationwide basis, the emissions from agricultural open burning constitute 0.1% or more of the total emissions for the following criteria pollutants: particulates, hydrocarbons, and carbon monoxide.

Table 8. TOTAL EMISSIONS OF CRITERIA POLLUTANTS RESULTING FROM AGRICULTURAL OPEN BURNING BY STATE AND NATIONWIDE[a]

Location	Particulates, metric tons/yr	Hydrocarbons, metric tons/yr	CO, metric tons/yr	NO_x, metric tons/yr
Alabama	1,400	1,600	8,100	160
Arizona	175	200	1,000	20
Arkansas	980	1,200	5,800	120
California	36,000	41,000	193,000	4,100
Colorado	1,200	1,400	7,200	140
Delaware	17	20	100	2
Florida	15,000	17,000	86,000	1,700
Georgia	7,500	8,600	44,000	880
Hawaii	10,000	12,000	59,000	1,200
Idaho	190	220	1,100	22
Kansas	4,600	5,400	27,000	540
Kentucky	490	2,900	580	58
Louisiana	16,000	19,000	95,000	1,900
Maine	280	330	1,000	33
Maryland	60	70	350	7
Massachusetts	26	30	150	3
Michigan	790	910	4,700	91
Minnesota	2,300	2,700	14,000	270
Mississippi	5,200	6,200	31,000	630
Missouri	1,500	1,800	9,100	180
Montana	1,300	1,500	7,600	150
Nebraska	2,600	3,000	15,000	300
Nevada	43	50	250	5
New Mexico	17	20	100	2
North Carolina	5,300	6,300	31,000	620
North Dakota	3,700	4,400	22,000	440
Ohio	1,200	1,400	7,100	140
Oklahoma	1,400	1,600	8,100	160
Oregon	4,100	4,800	24,000	480
Pennsylvania	580	690	3,500	69
South Carolina	120	180	1,900	18
South Dakota	2,300	2,700	13,000	270
Tennessee	520	610	3,100	61
Virginia	170	430	2,200	43
Washington	2,200	2,650	13,400	200
Wisconsin	1,200	1,300	7,100	150
Wyoming	290	340	1,700	34
National Total	111,000	132,000	662,000	13,200

[a]Based on assumed emission factors.

Table 9. RATIO OF CRITERIA POLLUTANT EMISSIONS RESULTING FROM AGRICULTURAL OPEN BURNING TO TOTAL STATE AND NATIONWIDE EMISSIONS[a]

Location	Particulates, %	Hydrocarbons, %	CO, %	NO_x, %
Alabama	0.11	0.21	0.19	0.04
Arizona	0.01	0.77	0.11	0.02
Arkansas	0.04	0.51	0.62	0.06
California[b]	2.4	1.3	1.7	0.17
Colorado	0.55	0.67	0.74	0.09
Delaware	0.04	0.03	0.04	0.001
Florida[b]	5.6	5.5	2.8	0.24
Georgia[b]	1.7	1.7	2.0	0.[illegible]
Hawaii[b]	15.	12.	19.	2.4
Idaho	0.11	0.24	0.29	0.04
Kansas[b]	1.2	1.6	2.5	0.21
Kentucky	0.08	0.01	0.04	0.01
Louisiana[b]	1.9	0.98	1.5	0.41
Maine	0.58	0.24	0.40	0.04
Maryland	0.01	0.02	0.01	0.002
Massachusetts	0.01	0.006	0.008	0.001
Michigan	0.10	0.12	0.11	0.004
Minnesota	0.79	0.61	0.71	0.48
Mississippi[b]	2.8	2.9	3.4	0.32
Missouri	0.19	0.40	0.44	0.04
Montana[b]	0.43	0.91	1.1	0.09
Nebraska[b]	2.4	2.2	2.6	0.27
Nevada	0.04	0.09	0.11	0.005
New Mexico	0.02	0.01	0.02	0.001
North Carolina[b]	0.99	1.3	1.6	0.14
North Dakota[b]	4.3	5.7	6.2	0.46
Ohio	0.06	0.11	0.12	0.01
Oklahoma[b]	1.1	0.41	0.59	0.07
Oregon[b]	2.2	1.9	2.1	0.12
Pennsylvania	0.01	0.07	0.08	0.002
South Carolina[b]	1.1	0.98	0.65	0.007
South Dakota[b]	1.9	2.7	3.1	0.49
Tennessee	0.11	0.15	0.19	0.01
Virginia	0.07	0.11	0.11	0.01
Washington	1.0	0.87	0.7	0.10
Wisconsin	0.47	0.35	0.42	0.10
Wyoming	0.[illegible]	0.98	0.91	0.04
Nationwide	0.01	0.00	0.00	0.00

[a]Based on assumed emission factors.
[b]States which have at least one ratio greater than 1%.

4. Population Exposed to High Pollutant Concentrations

To obtain a quantitative evaluation of the population influenced by a high concentration of emissions resulting from burning a typical agricultural field, the areas exposed to the time-averaged ground level concentration ($\bar{\chi}$) for which $\bar{\chi}/F \geq 1$ and $\bar{\chi}/F \geq 0.1$ were obtained by determining the area within the isopleth for $\bar{\chi}$,[17] and the number of people within the exposed area was then calculated by using a proper population density.

The representative population density used in the calculation of affected population was the average state population density, weighted by the amount of burning in each state. For hydrocarbons, which have source severity (S) greater than or equal to 1, the area and population exposed to a time-averaged ground level concentration for which $\bar{\chi}/F \geq 1$ and $\bar{\chi}/F \geq 0.1$ are shown in Table 10. For benzo(a)pyrene, which has $0.1 < S < 1$, affected area and population are shown only for $\bar{\chi}/F \geq 0.1$. In addition to the average exposed population, two extreme cases were also examined and these are listed in the same table. The extreme values were obtained by using the state population density of Massachusetts and Montana because these two states have the highest and lowest population density among the states where agricultural open burning is usually practiced.

It can be seen from Table 10 that for the average case, the population influenced by high ground level concentration is far below 20,000. However, it should be noted again that there may be some other POM compounds and trace metal elements emitted and not reported.

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[17] Turner, D. B. Workbook of Atmospheric Dispersion Estimates. U.S. Department of Health, Education, and Welfare, Public Health Service. Cincinnati, Ohio. 1969.

Table 10. AREA AND POPULATION EXPOSED TO POLLUTANTS FOR WHICH $\overline{1/F} \geq$ AND $\overline{1/F} \geq 0.1$[a]

Pollutant	Affected area, km^2		Exposed population, persons					
			Best case		Worst case		Average	
	$\overline{1/F} \geq 1$	$\overline{1/F} \geq 0.1$	$\overline{1/F} \geq 1$	$\overline{1/F} \geq 0.1$	$\overline{1/F} \geq 1$	$\overline{1/F} \geq 0.1$	$\overline{1/F} \geq 1$	$\overline{1/F} \geq 0.1$
Hydrocarbons	0.1	3	0.5	5	60	600	6	60
CO								
SO_2[b]	10^{-3}	0.3	0%	1	60	200	60	20

[a] Based on standard emission factors.

[b] Not applicable.

SECTION V

POLLUTION CONTROL TECHNOLOGY

A. STATE OF THE ART

The adverse impact on the environment from agricultural open burning can be reduced by proper fire and fuel management, meteorologically scheduled burning, or by the substitution of other alternatives.

Better fire and fuel management can result in a reduction in the amount of air emissions from open burning. The practice of meteorologically scheduled burning can facilitate maximum pollutant dispersion and reduce the ground level pollutant concentration. These two types of control and several alternatives to open burning are discussed below.

1. Fire and Fuel Management

It has been shown, in the burning of rice residues, that single line backfiring (wherein a fire progresses in a direction opposite to that of the wind) could reduce particulate emissions by approximately 50% over single line headfiring (wherein a fire progresses in the same direction as the wind) because backfiring provides a longer residence time for more complete combustion.[9] The backfire ignition technique was also recommended after an investigation of

plume rise and smoke characteristics from open field burning of agricultural residues.[18] However, it should be noted that the use of backfiring for fire management has limitations when fuel loading is low. In this case headfiring may become the only method that can produce an effective burn.

Among the field condition variables (air temperature, humidity, wind speed, fuel loading, and residue moisture content) it has been reported that residue moisture content is the primary variable controlling particulate emissions.[24,25] It was shown that residue with 10% moisture content emitted only 1/3 as much particulates upon burning as residue with 25% moisture content.[24] Therefore, the control of residue moisture in open burning can be used to reduce air emissions.

The residue moisture content is strongly related to solar radiation, relative humidity, air temperature, wind speed, and residue loading. In order to have low moisture content at the time of burning, the day and time of the day for burning should be carefully selected. To facilitate quick residue drying, it would be best to spread the residues evenly in the field. Uniformly spread residues also provide better disease control when burned.

2. Meteorologically Scheduled Burning

The pollutants, once emitted, can be effectively dispersed under certain meteorological conditions, and the environmental impact can be reduced to some extent. One way of achieving this is to permit burning only when the inversion base and the maximum mixing height are at prescribed levels,

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[18]Carroll, J. J. Determination of Temperature, Winds, and Particulate Concentrations in Connection with Open Field Burning. Final Report, Contract ARB-2114, Air Resources Board, State of California, November 1971.

and at specified wind velocities and directions. This type of control has been practiced in the San Francisco Bay Area for several years.[39,40]

In the Willamette Valley of Oregon, the climatology and predictive equations have been studied for management of smoke from field burning.[41] According to the study, the number of acres of field residue that may be burned on a given day without overburdening the air can be predicted. The predictions were based on the vertical temperature change, relative humidity, pressure gradient, wind speed, and existing visibility.

3. Mobile Field Sanitizer

One alternative to open burning is controlled incineration in a mobile field sanitizer. The development of these sanitizers was started in early 1970 by the Oregon State University, funded by the State Emergency Board. It was determined that the volatile portions of the crop residue burned in less than 1/2 second but 10 seconds were necessary to completely burn all the carbon particles.[42] The sanitizer was designed to burn all residue in its path within a self-sustaining combustion chamber. Particulate emissions were

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[39]Johnson, R. C., and R. A. James. Controlled Open Burning in the San Francisco Bay Area. J. Air Poll. Cont. Assoc., 20:530, August 1970.

[40]Osterli, V. P. Waste Disposal. In: Combustion-Generated Air Pollution, Starkman, E. S. (ed.). New York, Plenum Press, 1971.

[41]Bates, E. M. Smoke Management in the Willamette Valley. NTIS Publication No. COM-74-11377, May 1974.

[42]Research Relating to Agricultural Field Burning. Progress Report, Agricultural Experiment Station and Air Resources Center, Oregon State University, Corvallis, Oregon. February 1971.

estimated to be reduced by 80-90% and unburned hydrocarbon emissions by 99% when compared with open burning.[41]

The mobile field sanitiser consists of two sections as shown in Figure 5.[42] The front section is a converted combine which picks up straw and conveys it to the main incinerator. A large fan is fitted to the combine to supply combustion air to the single combustion chamber. Additional draft is supplied by a round stack on top of the fire box. A hopper on the front of the combustion chamber contains augers to convey fuel onto a stainless steel grate in the combustion chamber. Hinged steel tube drags are installed in the front and rear of the firebox to prevent fire spread. Because of the high temperature involved, the sanitiser is equipped with steel wheels and tires. A propane burner is used to provide the starting temperature.

Field testing in 1971 and 1972 on grass seed fields suggests that under ideal conditions the mobile field sanitiser will provide effective field sanitation and straw combustion with smoke emissions under the limits of the Department of Environmental Quality of the state of Oregon.[43] However, the reliability of the sanitiser in the control of weeds, pests, and disease, and in the thermal stimulation of soil for various crop species is still questionable.[44] Because of engineering and economic problems, the field sanitiser is still not commercialised, despite the banning of open burning in the Willamette Valley, effective January 1, 1975.

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[41] Farmer Alternatives to Open Burning: An Economic Appraisal. Special Report 316, Agricultural Experiment Station, Oregon State University, Corvallis, Oregon. October 1971.

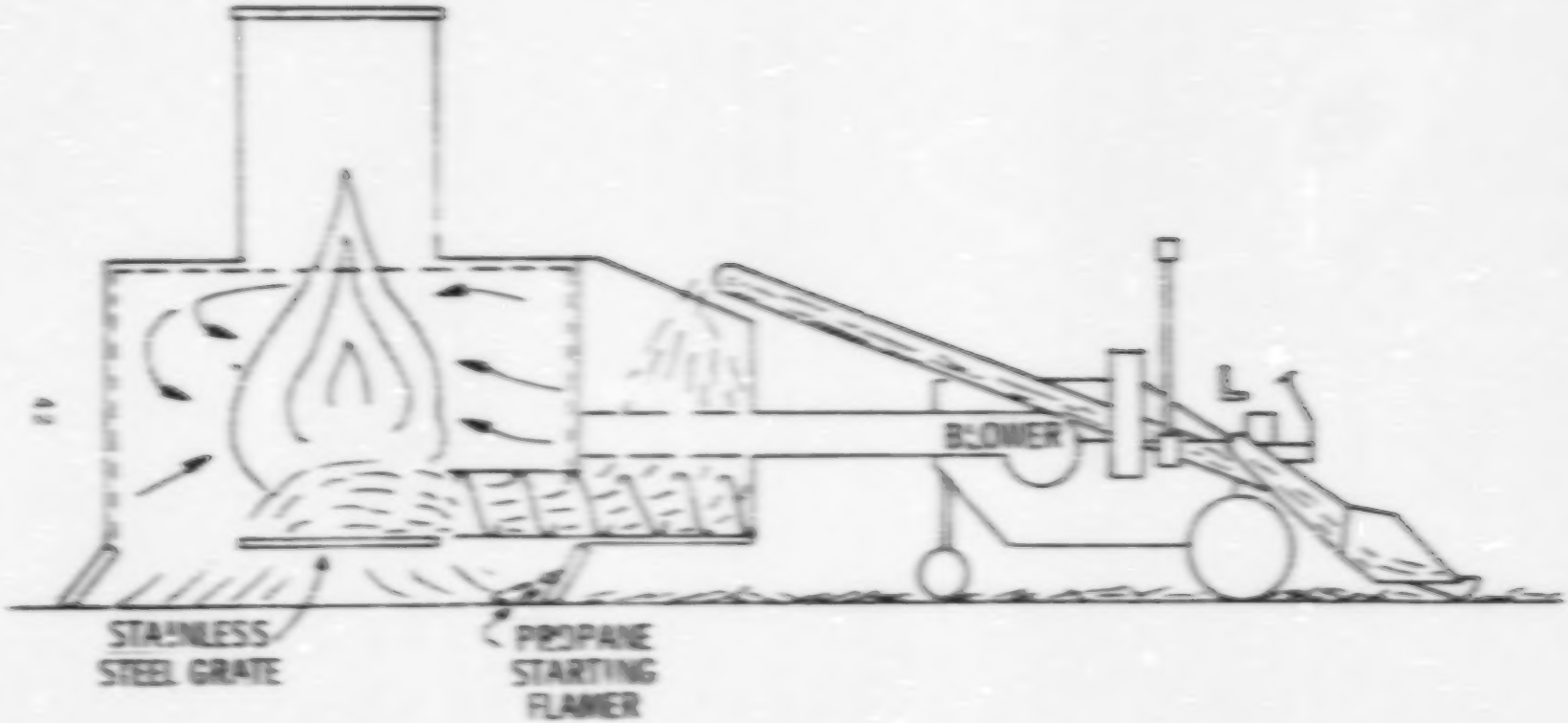

Figure 5. Schematic diagram for mobile field sanitizer.[47]

The field sanitiser was also tested in California rice and barley fields in 1971 and 1972.[44] and some difficulties were experienced. Due to the high silica content of rice straw, machine operation was unsatisfactory. Wild fires occurred in the field operation. The study also concluded that high particulate emission levels will still be a problem unless some provisions were made to remove particulates at the incinerator discharge. If the technical problems can be solved, the field sanitiser with its controlled temperature can provide more uniform and complete weed/disease control than can be attained by open burning.

4. Other Alternatives

Field burning can be used to simultaneously accomplish field sanitation, residue removal, and residue disposal. In the grass seed land in the Willamette Valley of Oregon, field burning also provides a thermal treatment to the soil which raises the production yield substantially. Therefore, in the study of alternatives, the above-mentioned factors must be considered.

The most common method of disposing of crop residues is to incorporate the material directly into the soil. This can be accomplished by disking or by chipping or shredding for subsequent working into the soil. The main problems mitigating against the extension of soil incorporation of the remaining residues now burned in some areas of the country are: (1) poor soil conditions for cultivation as exist

[44]Miller, G. E., and J. R. Goss. Study of Abatement Methods and Meteorological Conditions for Optimum Dispersion of Particulates from Field Burning of Rice Straw: Rice Straw Incinerator Evaluation. Publication No. PB 230 405, June 1973.

for California rice where the water table is high and the residue occurs late in the year when temperatures are low, biodegradation is slowed, and disease or pest problems may be great; (2) the occurence of bulky materials not capable of incorporation, such as large prunings, or removed fruit trees; (3) a requirement for rapid removal of the residue to permit planting of the following crop; and, (4) possible soil nitrogen depletion due to the residue decomposition.

Another alternative to field burning is the mechanical removal of residues. This method is generally expensive unless the residue commands a satisfactory price. Oregon State University has conducted extensive research on the potential uses of residues generated in the Valley. Among the products found to be technically feasible were paper, hardboard, insulation material, animal feeds, fuel, and microbial protein.[44] At the present time, a major crop residue is used for stubble-mulch farming to protect fallow lands against the erosive forces of wind and water.

In the event that field burning is not employed, chemical methods would be required to control weeds, disease, and pests. The subsequent effect in air and water pollution resulting from the application of herbicides, fungicides, and pesticides would also have to be evaluated.

In grass disease research, an intensive program of testing available fungicides for control of major grass disease, underway for years, has not produced a practical chemical control.[45] More stringent federal standards have decreased the number of new fungicides being developed and fewer new chemicals are available for further evaluation.

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[44]Field Burning, Agricultural Experiment Station, Oregon State University, Corvallis, Oregon. February 1971.

B. FUTURE CONSIDERATIONS

Due to the continuous expansion of urban communities, the reduction in agricultural land, and the increase in the intensity of agricultural planting, pollution controls on open burning as described in Sections V.1 and V.2 may not be sufficient to reduce the environmental impact in the future. Further research is therefore needed in the following areas in order to reduce the practice of agricultural open burning: (1) improve the mobile sanitiser for better control of disease and weeds, for maintaining crop yields, and for safer operation; (2) study the environmental impact of the extensive use of chemical control of disease, weeds, and pests; (3) identify the domestic and foreign markets for utilization of crop residues; and, (4) develop more effective and less harmful (to mankind) means of chemical control of disease, weeds, and pests.

Straw residue is high in cellulose and can be used in manufacturing many different products. In a few years, this straw may be a very valuable raw material for other industries.[46] In the future, the solution to open field burning of cereal crop and grass seed residues may be a combination of straw utilization and mobile field sanitation.

Until less harmful and more effective chemical controls are available and until other economically viable techniques for residue utilization or disposal are developed, control of the environmental degradation of air quality will depend on fire and fuel management and on meteorologically controlled burning.

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[46] Sherman, C. J. Is the industry Going Up in Smoke? Crops and Soils Magazine, 25:10, April 1974.

SECTION VI

GROWTH AND NATURE OF THE SOURCE

Open burning is one of the principal methods of disposing of agricultural wastes. Despite the continuing growth in crop harvest, agricultural open burning has been declining since 1969 due to increasing awareness of its contribution to air pollution and development of waste utilization, chemical control of weeds, pests, and diseases, and modern tillage and fertilization practices. EPA's estimated agricultural open burning was 29 x 10^6 metric tons (33 x 10^6 tons) for 1969. This figure dropped to 13.2 x 10^6 metric tons (14.6 x 10^6 tons) for 1973.[14]

In some cases there are no alternatives to open burning at the present time. Examples are sugarcane burning in Florida, Louisiana, and Hawaii; grass seed burning in Oregon, Washington, Arizona, and Idaho; and rice and barley residue burning in California.

In 1971, the Oregon State Legislature passed a bill banning open burning in the Willamette Valley, effective January 1, 1975. However, due to the unavailability of effective alternatives, it is possible that the lawmakers will eventually reverse their decision.[13]

Although agricultural open burning will continue to decline, the burning in several areas of the country will continue until more effective and less harmful chemical control of pests, weeds, and disease is available, and until other economically viable techniques for residue utilization or disposal are developed.

SECTION VII

APPENDICES

A. Sample Calculations for Data on Burning Shown in Table 4.

B. Equation Derivation and Input Data

APPENDIX A

SAMPLE CALCULATIONS FOR DATA ON BURNING SHOWN IN TABLE 4

The burning data were usually reported in nonmetric units. Calculations were made using nonmetric units, and then the results were converted to metric units.

Total number of states in which agricultural open burning is practiced[12] = 37

Total burning in the U.S.[14] = 14,600 x 10^3 tons/yr

Total burning reported for 18 states[12,14,15] (excluding the nonsugarcane burning in Florida for which data were not available) = 11,746 x 10^3 tons/yr

Total burning in the remaining 19 states (including the nonsugarcane burning in Florida) = 14,600 x 10^3 - 11,746 x 10^3

= 2,854 x 10^3 tons/yr

For Florida

Total burning was calculated by estimating the nonsugarcane burning and adding that value to the sugarcane burning, the latter calculated from reported information.

Nonsugarcane crop average = $2{,}089 \times 10^3$ acres[47]

$$\text{Nonsugarcane burning} = 2{,}054 \times 10^3 \text{ tons/yr} \times \frac{2{,}089 \times 10^3 \text{ acres}}{161{,}531 \times 10^3 \text{ acres}}$$

$$= 37 \times 10^3 \text{ tons/yr}$$

where $161{,}531 \times 10^3$ acres represents the total crop average in the remaining 19 states.

Sugarcane acres burned	= 265×10^3 acres/yr[11]
Tons sugarcane burned per year	= 7 tons/acre[11]
Sugarcane burning	= $1{,}855 \times 10^3$ tons/yr
Estimated nonsugarcane burning	= 37×10^3 tons/yr (calculated above)
Total burning	= $1{,}893 \times 10^3$ ton/yr or $1{,}716 \times 10^3$ metric tons/yr

[47] Agricultural Statistics. Statistical Reporting Service, U.S. Department of Agriculture, 1974.

For Arizona

State crop acreage = $1,251 \times 10^3$ acres[17]

Burning = $2,854 \times 10^3$ tons/yr $\times \frac{1,251 \times 10^3 \text{ acres}}{161,531 \times 10^3 \text{ acres}}$

= 22×10^3 tons/yr or 20 metric tons/yr

Estimated fuel loading = 2 tons/acre[14]

Area burned = $\frac{22 \times 10^3 \text{ tons/yr}}{2 \text{ tons/acre}}$ = 11×10^3 acres/yr or 4.5×10^7 m^2/yr

APPENDIX B

EQUATION DERIVATION AND INPUT DATA

1. DEVELOPMENT OF EQUATION (IV-2)

The behavior of plumes from agricultural open burning is different from that of plumes from elevated stacks in the following respects: (1) the emissions from open burning are a progressing line source, with large amounts of heat release, rather than a near-point source as is the case emissions from elevated stacks; and (2) the only driving force for plume rise in the case of open burning is the buoyancy force created by the burning process. Thus, the effective plume height is totally controlled by environmental factors (especially wind speed). In stack emissions, the buoyancy rise is only one of the factors used in estimating the effective emission height.

A number of empirical equations are available in the literature for predicting the plume rise in stack emissions. However, due to the differences between the two types of emission sources, the application of these equations to open burning becomes questionable.

After examining the relative ground level concentration between a one-unit and a ten-unit power plant, it was concluded that due to the separation of emission stacks, the

plume rise becomes proportional to the 0.35 power of heat emission.[48] This separation of emission points in the power plant is similar to the line source in the agricultural open burning. Thus, an equation similar to the Lucas, Moore, and Spurr formula[49] was used to predict the effective emission height, H, in this document:

$$H = kQ_h^{0.35} / \bar{U} + c \qquad \text{(B-1)}$$

where Q_h = heat emission rate relative to ambient temperature, kcal/s

$\bar{U}$ = average wind speed, m/s

k = a system parameter, $m/kcal^{1/4}s^{1/4}$

c = the flame height, m

A relationship of this type is essentially unchanged for wind direction normal to or in line with the burning line. The larger buoyant effect for in-line winds approximately compensates for the dilution effect of wind normal to the burning line. However, it should be noted that although the wind direction does not affect the plume rise, it does change the emission rate (due to the difference between backfire and headfire).

2. EVALUATION OF THE SYSTEM PARAMETER, k

The value of the system parameter, k, in Equation (B-1) was estimated using the data listed below:

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[48] Thomas, F. W., S. B. Carpenter, and F. E. Gartrell. Stacks - How High? J. Air Poll. Cont. Assoc., 12:198, May 1962.

[49] Lucas, D. H., D. J. Moore, and G. Spurr. Intern. J. Air Water Poll. 7:473, July 1963.

Size of field:[14]	2,500 m^2 or 50 m x 50 m (0.25 acre or 160 ft x 160 ft)
Fuel loading:[14]	6.72×10^{-4} metric ton/m^2 (3 tons/acre)
Fire propagation rate:[14]	4.6 m/min (15 ft/min)
Fuel heating value:[3]	3,000 kcal/kg or 12.56 MJ/kg (5,400 Btu/lb)
Flame height:[4]	2 m (7 ft)
Effective emission height:[14]	210 m (690 ft)
Wind speed:[14]	1.34 m/s (3 miles/hr)
Burning:[4]	starts from one side of the square field.
Heat loss to soil, ash, and water evaporation:[4]	20%

Q_h was calculated by the following formula:

Q_h = (length of one side of the square field) x (fire propagation rate) x (fuel loading) x (heating value) x (1.0 - 0.2) (B-2)

With the listed data above, Q_h becomes:

Q_h = 50 m x 4.59 m/min x 1 min/60 s x 6.72×10^{-4} metric ton/m^2 x 3,000 kcal/kg x 0.8 x 1,000 kg/metric ton = 6,169 kcal/s

[4]Assumed.

With Q_h, H, and σ known, Equation (B-1) was then used to back-calculate k value.

$$k = \frac{(H-\sigma)\ \bar{u}}{Q_h^{1/4}} = 31.5\ m^2/s^{1/4}\ kcal^{1/4} \qquad (B-3)$$

Note that this k value is dimensional and the value shown is based on the quantity of Q_h in units of kcal/s, and H and σ in meters. Conversion factors are presented in Section IX.

1. Derivation of Equations (IV-4) and (IV-5)

The maximum ground level concentration (χ_{max}) calculated from Equation (IV-1) is the value for short term averaging time during which the Gaussian plume diffusion equation is valid. The short term averaging time was found to be 3 minutes in a study of published data on lateral and vertical diffusion.[59] The estimate of maximum ground level concentrations for time intervals greater than 3 minutes can be obtained by using the following formula for a continuously emitting source:[17]

$$\bar{\chi}_{max} = \chi_{max} \left(\frac{t_{max}}{t_i} \right)^{0.17} \qquad (B-4)$$

where t_i = the averaging time

t_{max} = the short term averaging time (= 3 minutes)

In the case of agricultural open burning, a field is burned for only a short duration each time, ranging from a few minutes to several hours. If the averaging time is smaller

[59]Nonhebel, G. Recommendations on Heights for New Industrial Chimneys. J. Inst. Fuel, 33:479, July 1960.

than the burning duration, then this source can be treated as a continuously emitting source, and Equation (B-4) can be used to obtain the time-averaged maximum ground level concentration. Note that Equation (B-4) is essentially the same as Equation (IV-4).

If the averaging time is greater than the burning duration, then the concentration has to be averaged over the burning duration (as a continuously emitting source) and then averaged over the averaging time (as a non-continuous source). This treatment can be expressed by the following equation:

$$\bar{\chi}_{max} = \chi_{max} \left(\frac{t_{max}}{t_2}\right)^{0.17} \cdot \frac{t_2}{t_1}$$

$$= \chi_{max} \cdot t_2^{0.83} \cdot t_{max}^{0.17} / t_1 \qquad \text{(B-5)}$$

where t_2 = the burning duration

Equation (B-5) so derived is the same as Equation (IV-5) which is applicable when $t_1 > t_2$.

4. INPUT DATA FOR CALCULATION OF χ_{max}

The maximum ground level concentration, χ_{max}, of pollutants resulting from agricultural open burning was described in Section IV.D.1 of this document. Input data used to calculate U_m, U_h, H, and χ_{max} are provided below for the average, worst, and best cases.

a. Average Case

The input data used for the average case are the same as those listed in Section 2 of Appendix B except for the following variables:

Size of field:[13, 35]	10^5 m^2 (25 acres)
Wind speed:[a]	4.5 m/s (10 miles/hr)

b. Worst Case

The input data used for the worst case are the same as those listed in Section 2 of Appendix B except for the following variables:

Size of field:[13]	80 x 10^5 m^2 (200 acres)
Fuel loading:[12]	2.69 x 10^{-3} metric ton/m^2 (12 tons/acre)
Wind speed:[b]	9.0 m/s (20 miles/hr)

c. Best Case

The input data used for the best case are the same as those listed in Section 2 of Appendix B except for the following variables:

Size of field:[13]	10^4 m^2 (2.47 acres)
Fuel loading:[12]	2.24 x 10^{-4} metric ton/m^2 (1 ton/acre)
Wind speed:[b]	0.9 m/s (2 miles/hr)

[a]National average wind speed.
[b]Estimated value.

SECTION VIII

GLOSSARY OF TERMS

AFFECTED POPULATION - The number of people around a representative source who are exposed to a source severity greater than 0.1 or 1.0 as specified.

BACKFIRE BURNING - Fire progression in a direction opposite to that of the wind.

BURNOUT - Smokeless combustion which occurs after oxygen has diffused to a gas-solid interface of the nonvolatile portion of combustible material (often referred to as char).

CRITERIA POLLUTANT - Pollutant for which ambient air quality standard has been defined (these are: particulate, hydrocarbons, carbon monoxide, sulfur dioxide, and nitrogen oxides.

EMISSION FACTOR - Quantity of emissions per quantity of mass burned.

EXPOSURE FACTOR - A value used to indicate the combination effect of amount of burning and state population.

FUEL LOADING - Mass of material burned per unit of area burned.

HEADFIRE BURNING - Fire progression in the same direction as the wind.

NONCRITERIA POLLUTANT - Pollutants for which ambient air quality standards have not been defined.

POLYCYCLIC ORGANIC MATTER - Heavy hydrocarbons which may have carcinogenic properties.

REPRESENTATIVE SOURCE - An agricultural open burning field defined for use in calculating the source severity.

SANITIZER - Mobile field unit used for controlled incineration of residue.

SMOKE - A suspension of submicron particulates consisting of solid and liquid aerosols.

SOURCE SEVERITY - An indication of the hazard potential of an emission source.

THRESHOLD LIMIT VALUE (TLV) - Refers to airborne concentrations of substances and represents conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect.

SECTION IX

CONVERSION FACTORS AND METRIC PREFIXES[1]

Conversion Factors

To convert from	to	Multiply by
joule (J)	British thermal unit (Btu)	9.479×10^{-4}
joule (J)	cal	2.388×10^{-1}
kilogram (kg)	pound-mass (lb mass avoirdupois)	2.205
kilogram (kg)	ton (short, 2,000 lb mass)	1.102×10^{-3}
kilometer^2 (km^2)	mile^2	3.861×10^{-1}
meter	feet	3.281
meter	inch	3.937×10^{1}
meter	mile	6.215×10^{-4}
meter^2 (m^2)	acre	2.470×10^{-4}
meter^2 (m^2)	hectare	1.000×10^{-4}
meter^3 (m^3)	feet^3	3.531×10^{1}
metric ton	pound-mass	2.205×10^{3}
metric ton	ton	1.101

[1]Standard for Metric Practice. American Society for Testing and Materials. Philadelphia. ASTM Designation: E-380-76. February 1976. 17 p.

Metric Prefixes

Prefix	Symbol	Multiplication factor	Example
mega	M	10^{6}	1 MJ = 1 x 10^{6} joules
kilo	k	10^{3}	1 kg = 1 x 10^{3} grams
milli	m	10^{-3}	1 mg = 1 x 10^{-3} gram
micro	μ	10^{-6}	1 μm = 1 x 10^{-6} meter

SECTION X

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